Assessing the Army Power and Energy Efforts for the Warfighter

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Contents

Executive Summary

In this paper we review some of the landscape of research and development on power and energy as it pertains to the needs of the Army warfighter. We focus on the battlefield and consider questions related to vehicles, dismounted soldiers, and forward operating bases. The literature in the overall field of energy research is immense; we make no attempt to review all these reports but rather have looked at a few selected studies that focus on the military challenges. The context of the study is twofold: the National need to reduce the use of petroleum-based fuels and the Army's need to reduce the logistical burden and hazards of moving said fuels on the battlefield. The conflicts in Iraq and Afghanistan have highlighted the danger inherent in transporting supplies over terrain that is difficult to render safe from terrorist raids and hidden explosives. The Army seeks to reduce this dependence by improving the fuel efficiency for uses that cannot now be entirely supplied by alternatives. These efforts will also provide the opportunity to save a great deal of money and reduce the number of personnel in the logistics chain. Needless to say, there will still be convoys carrying other supplies to forward bases. However, any reduction in the amount of supplies convoyed will be desirable.

We find, in the literature, many good studies on the military problem such as those done by the Defense Science Board, the Logistics Management Institute, and the National Research Council. The findings show that there are many technologies ready for adaptation for vehicles and dismounted soldiers. These are being improved upon incrementally in current science and technology (S&T) programs. Technology for forward operating bases (FOBs) has, until recently, not been a high priority area. However, there are some concepts that appear ready to be integrated and adopted through advanced development and technology demonstrations. The work on FOBs is a good example of a holistic approach to the problem; that is, considering a variety of approaches and integrating them into a system. Using computerized microgrids for sharing and leveling electricity demand on such bases will be a part of the solution.

We have studied documents and interviewed a number of Army technologists to understand the current S&T program. The program is conducted in several Army laboratories as well as by the Army Research Office (ARO). The laboratories are, in general, focused on raising the readiness level of projects already in research or

development. ARO is pushing the frontiers in its portfolio of basic research. We believe that these programs would benefit from increased oversight and coordination.

The Research, Development, and Engineering Command of the Army Materiel Command has established two Technology Focus Teams that address this problem. One concentrates on electrical and electronics efforts and the other covers logistical and mobility technologies. Neither has any role in the work on power and energy being done at the Corps of Engineers.

We believe there are two approaches to improving the efforts in the several laboratories. One is improvement in the coordination role of the Deputy Assistant Secretary of the Army for Research and Technology. The second is conducting a formal technology forecasting effort using convergence concepts that would result in a roadmap to guide the evolution of the Army S&T program. We also recommend doing more long-term basic and exploratory research looking for significant breakthroughs in some of the challenges. We realize that this is risky in an area that has received so much research attention in the past. The hope is that with the technology forecast some new and unexpected possibilities will emerge.

Introduction

Armies are dependent on power and energy. When these resources for any reason are not available on the front lines, everything is affected. The importance of petroleum-based liquid fuels in warfare became evident in 1892 when Rudolph Diesel developed his four-cycle spark ignition engine.[1] By 1909 the French had switched from coal to oil-fired ships. Japan's inability to obtain sufficient petroleum to supply their war machine was one of the major reasons for their need to expand their dominion to include sources of petroleum. The logistics of warfare in World War II were a controlling factor in critical times. For example, in the European theater General Patton's Third Army, on its dash to Germany, ground to a halt when it ran out of fuel. Similar shortages affected the Germans in the latter stages of the war, especially during the Battle of the Bulge. Fuel supply remains a challenge to logisticians in today's conflicts.

The Abrams main battle tank is reported to consume a gallon of fuel for every half mile traveled. The dismounted soldier is overburdened with nonstandard batteries; one or more is needed for each different device using electricity. Field commanders have long been seeking lighter, longer-lasting, and less expensive batteries that supply substantially more power per unit weight. These demands have intensified with the revolution in electronics that has brought various new capabilities in the form of devices that can enable vision at night, use lasers to designate targets at a distance, power small robotic vehicles, provide sensing and communications, and so on. More such devices are in development. It is therefore not surprising that the U.S. Army Training and Doctrine Command (TRADOC)

[1] This historical material is from Kenneth Macksey, "Technology in War," Prentice Hall Press, NY, 1986. See pages 47, 50, 57, and 144.

has recently made improvements in power and energy usage as one of the most desired outcomes needed by the warfighter.[2]

Research into improved efficiency in the Army's use of energy has a long history. Some of this work has been in engine design, high power electronics, environmental control systems (ECUs), distribution, alternative power conversion (fuel cells and Stirling devices), and a considerable effort on chemical storage batteries. Not until recently has the effort broadened to include alternative sources of energy with much improved capabilities and efficiencies. Some of this is being done in parallel developments in the private sector; e.g., solar and wind energy, compact batteries for computers and hand-held communications devices. There has been much progress and more is likely in the near future. In this report we review the Army's technology efforts to weigh the balance and distribution of the effort and to place it in the perspective of the broader energy world.

We begin with a background section that stresses the importance of oil over the years in geopolitics. This is followed by a review of some of the many studies on power and energy in the military. Next is a presentation of the current technical programs being conducted across the Army. Then we have a discussion of basic research, primarily at the Army Research Office, and a look forward with emphasis on technology forecasting. Finally we draw conclusions and assess the findings of our study and close with recommendations for the office of the Deputy Assistant Secretary for Research and Technology.

Background

A very recent book by Reynolds details the critical role oil has played and is playing in geopolitics.[3] The author begins with a discussion of the importance of imported oil in the US economy. He discusses the dollar outflow to oil producers around the world, the impact of this outflow on the trade deficit, and on the return of the dollars as foreign investment in the US. This leads into a summary of the geopolitics of oil production with an emphasis on the Middle East. This is a history going back to the beginning of the last century. The oil market governed US relations with Saudi Arabia, Iran, and Iraq. The overthrow of the Shah of Iran turned the relationship of Iran with the US on its head. We maintain the support of the Saudis but only tenuously. Reynolds ascribes the two wars in Iraq ultimately to the oil dependence of the US. The US oil industry that began in Pennsylvania and flourished under the Rockefellers prospered until the demand outstripped US capacity. This was driven by the growth of the automobile and highway transportation. By 1973 the US had reached the capacity for domestic oil production. The Yom Kippur War and the US support of Israel led to the 1973 Arab oil embargo.

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[2] Col. R.C. Effiinger, *Warfighter Challenges/Warfighter Outcomes*, Presented at the Technology Planning Conference, Army Research Laboratory at Adelphi, MD, May 2010; Army Capabilities Integration Center, Research, Development and Engineering Command, and the Deputy Chief of Staff, G-4, *Power and Energy White Paper*, published by TRADOC, Fort Monroe, VA, April 2010.
[3] Lewis Reynolds, *America the Prisoner*, Relevance Media, Inc., Charlotte, NC, 2010.

Curtailment of oil shipments produced disruption in the daily lives of American consumers – from long lines waiting at the gas pumps to rising prices for gasoline. In 1979 the Islamic revolution in Iran deposed the Shah, Saddam Hussein took power in Iraq, and the USSR invaded Afghanistan. The geopolitics was no longer the same.

Rising oil prices on the international market were supported by increasing demand in the US, in China, and elsewhere. In the US, drilling could not keep up. Alternatives to an oil economy were pursued. Oil as a source of fuel (as opposed to a feedstock for the chemical industry) can be replaced by a number of sources depending somewhat on the end use. For electric power generating plants, coal, natural gas, and nuclear power had replaced oil. Coal now supplies 49% of US power plants; nuclear provides about 20% from 104 commercial reactors in the US. The US no longer relies on imported oil for power generation on the national power grid. But coal, nuclear, and natural gas are unlikely options for the Army; nor are they candidates for vehicles (or for the dismounted soldier). Except for nuclear, all energy sources arise directly or indirectly from the sun. Petroleum is one such. Others include solar, wind, and biomass. Wind turbines are beginning to spring up in various parts of the country. Solar units for home use create power either by direct conversion of the sun's energy into heat by rooftop units or by direct generation of electricity using photovoltaic cells.

Currently, the military is the largest single consumer of energy in the United States. On the battlefield, purchasing and transporting fuel is a major expense in dollars and in support troops. Convoys have become very dangerous. The Army wants to reduce the amount of supplies requiring convoys and hence the exposure of the personnel escorting them. It also wants to reduce the expenses associated with oil on the battlefield. This need coincides with the National need for reducing energy dependence on foreign sources. This dependence can be minimized by improving the efficiency of the systems using petroleum-based fuel and by replacing, for some applications, petroleum-based fuel with alternatives such as wind and solar – both direct conversion to heat and by producing electricity (by photovoltaics). We discuss later in this paper the conversion of waste to energy at forward installations. A related activity in the United States is the production of liquid fuels by fermentation (alcohol from corn) or by thermal and chemical conversion of non-food crops such as switch grass.[4]

In addition, biomass, derived from many sources, can be converted by fermentation as in the case of converting corn to alcohol or by thermochemical processes to synthetic gas – carbon monoxide and hydrogen (syngas). Syngas can then be converted to hydrocarbons or alcohols using catalysts and the resulting mixture separated by the same processes as are used today in oil refineries. Syngas can also be used directly as a fuel for generators. Commercial ventures began in Germany in World War II were based on research done in the 1920s. Germany had a dearth of oil and needed to change raw materials to coal and natural gas. German chemists had invented the process to make syngas and make hydrocarbons (the Fischer-Tropsch process). After the war, South Africa developed the process further. After the 1979 revolution in Iran, the Congress created the Synfuels Corporation (SFC) to develop the process to replace petroleum raw materials. However,

[4] For example see the interest by the U.S. Navy in *Federal Times, Newswatch*, for October 18, 2010.

the SFC experiment came to naught as a world-wide recession and intensified efforts on energy conservation reduced the price of crude oil by one third. Synfuels work was abandoned. However, the process technology is useful in other biomass conversions.

Along with the DoD, the US Departments of Energy and Agriculture are working on a variety of biomass conversions. The use of corn to produce alcohol is commercial but, Reynolds claims, there are limits to how much fuel can be produced this way. Other options include the use of waste products or growing high yield crops. Biomass from wood residues in forests and wood processing, combined with residues from farming, are one source. High potential crops are typically grasses such as switch grass.

Biomass as a source of energy is the subject of a great deal of research and development and may ultimately produce liquid fuels to replace oil-based fuel. A new paper by Coffey[5] reviews some 15 technologies for replacing the use of oil for transportation. He concludes that, "if necessary, the United States can manufacture the transportation fuels it needs." In terms of process efficiency and capital cost for production plant, he finds that steam reforming of methane to make methanol is the most attractive alternative. Methanol can then be transformed into gasoline. The various approaches to biofuels are limited both by available supply and high capital cost for the production facilities. For high energy, high power engines such as the military requires, he concludes that internal combustion engines will be the ones of choice. Coffey believes that biomass-based fuels may very well occupy a number of niche applications but by themselves cannot solve the total replacement of oil for transportation There seems little doubt that the biomass fuels can be utilized by current engines for ground vehicles. Gasification technology is used in the waste to energy projects being explored by the military. These are discussed in some detail later in this paper. We turn now to several studies on fuel efficiency by the Army for vehicles, for the dismounted soldier, and for isolated combat operations posts.

Selected Recent Studies

The world of energy research is vast, encompassing many scientific and engineering fields ranging from the conventional to the esoteric. When one tries to make a list of energy-related activities it becomes apparent some sort of systematic approach is necessary. (A search of "energy research" on Google turns up 110 million hits.) What is needed for the present study is an analysis that moves from the universe of energy research down to a few high priority needs of the Army.

There are in the literature very many studies and reviews of power and energy in the military, some by outside groups including the Defense Science Board (DSB), the Logistics Management Institute (LMI), and the National Research Council (NRC) of the National Academies (of which we consider only a sample of the work of the NRC). A

[5] Timothy Coffey, *A Primer on Alternative Transportation Fuels*, DTP 74, (Washington, D.C.: Center for Technology and National Security Policy, National Defense University, September 2010).

study by the Army Research Laboratory (ARL) in the 1990s provides some of the basis for subsequent studies.[6]

In a study by the Defense Science Board, the top ten battlefield fuel users as of 2001 were as presented in Table 1 below[7].

Today's Top 10 Battlefield Fuel Users

SWA scenario using current Equipment Usage Profile data

Of the top 10 Army battlefield fuel users, only #5 and #10 are combat platforms

1.	TRUCK TRACTOR: LINE HAUL C/S 50000 GVWR 6X4 M915
2.	HELICOPTER UTILITY: UH-60L
3.	TRUCK TRACTOR: MTV W/E
4.	TRUCK TRACTOR: HEAVY EQUIPMENT TRANSPORTER (HET)
5.	*TANK COMBAT FULL TRACKED: 120MM GUN M1A2*
6.	HELICOPTER CARGO TRANSPORT: CH-47D
7.	DECONTAMINATING APPARATUS: PWR DRVN LT WT
8.	TRUCK UTILITY: CARGO/TROOP CARRIER 1-1/4 TON 4X4 W/E (HMMWV)
9.	WATER HEATER: MOUNTED RATION
10.	*HELICOPTER: ATTACK AH-64D*

List produced by CASCOM for TAA-2007 using FASTALS for SWA. For more details, see backup slides.
Blue: Supply transport vehicles; Green: field kitchen systems; Red: weapons platforms

Table 1. This list was derived from a combat scenario in Southwest Asia using the Force Analysis Simulation of Theater Administrative and Logistics Support (FASTALS) developed by the Army's Combined Arms Support Command. (These results will vary depending on the battlefield scenario. For example the Abrams main battle tank has seen little service in Afghanistan.)

The ARL studied the potential savings in fuel for combat vehicles. Ten combat vehicles were studied, including the Abrams main battle tank, the Bradley Fighting Vehicle, and the Apache attack helicopter. The study highlighted the much higher cost of fuel delivered on the battlefield compared to the price at the refinery – sometimes as much as $600 a gallon. The increased cost is in the logistics personnel and the extra fuel needed to transport the fuel to the user. A chart in the briefing shows:

> For every dollar spent on fuel delivered to an Army terminal in the U.S., ten dollars are spent on the battlefield [to move the fuel] for personnel costs for active troops, and another six dollars for reserve personnel costs.

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[6] *The Impact of Fuel Efficiency on the Army After Next*, Army Research Laboratory briefing FEAAN1a , October 1998, , available from the Office of the Director, Sensors and Electron Devices Directorate, Army Research Laboratory, Adelphi, MD.

[7] See reference 14, p. 43.

The ARL study predicted an increase in efficiency of 75% overall from known technology developments for all ten of the combat platforms. Technical areas included, among others, engines, transmissions, and light-weight materials for structural components and armor. The results highlighted the opportunity for cost savings and for improvement in the "tooth to tail" ratio on the battlefield.

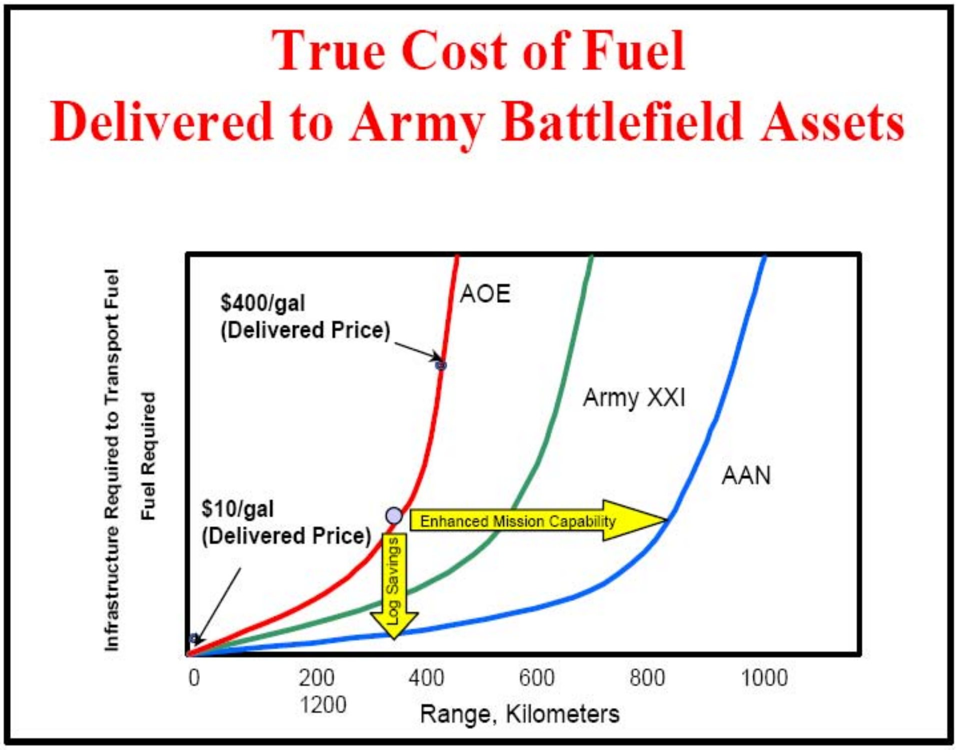

Table 2. Chart from the ARL study (Ref. 6) and cited by the DSB (See ref. 13, p. 18.)

There have been several studies on power and energy for the Army by the National Research Council (NRC). Two studies focused on the needs of the dismounted soldier. The 1997 study[8] discussed both the potential sources of power and the potential reduction of power demand by the various systems carried by the soldier. The 2004 study[9] is a very thorough review of power sources and loads (or sinks) for the dismounted soldier and for some sources for FOBs; e.g., for generators. It considers batteries, with emphasis on lithium ion systems and fuel cells, especially proton exchange membrane and solid oxide systems, and hybrids of fuel cells and batteries, sometimes coupled to a capacitor. Technology readiness levels are given as of 2003. Detailed comparisons of performance are presented in numerous graphs and tables. The study also considered power sinks for such as laser designators, microclimate cooling, and the proposed exoskeleton. This report is a primer on the state of the art as of 2004.

[8] Board on Army Science and Technology, *Energy-Efficient Technologies for the Dismounted Soldier,* National Research Council, National Academies Press, Washington, D.C., 1997).
[9] *Meeting the Energy Needs of Future Warriors,* Board on Army Science and Technology, National Research Council, National Academies Press, Washington, D.C., 2004.

For any assessment of the cost of power and energy on the battlefield, it is important to determine the fully burdened cost of fuel (FBCF). The fundamental assumptions in calculating fuel costs have been a matter of debate. A parallel and related issue is the nature of the fuel required. As a general rule, military logistics typically favors simplicity, hence the ubiquitous use of JP-8 and its variants as an all purpose fuel. The use of JP-8 therefore determines the cost and the availability of fuel. Estimates of this cost vary over at least two orders of magnitude.

There are numerous important variables and assumption which underpin the FBCF. The first is the phase of operations. During expeditionary operations where facilities are negligible, fuel may have to be flown in by helicopter. A 2001 Defense Science Board Task Force paper, "More Capable Warfighting through Reduced Fuel Burden," estimated that under a worst case, three-staged, re-supply scenario using CH470D aircraft, the cost of air delivery would be approximately $400 per gallon. (However, see the higher figure of $600 a gallon from the ARL study.) During sustained operations, where fuel can be brought in by overland transport, this study calculated the FBCF at $40-$50 per gallon. Finally, during post-combat stabilization operations where local facilities are gradually brought back online, the cost might be expected to drop further.

A second major variable is the type of unit or facility using the fuel. In the section on Forward Operating Bases (see page 20) we discuss the progression from Corps level installations to major forward operating bases (FOBs) to smaller FOBs and finally to combat outposts (COPs). The availability of fuel and the uses to which it is put vary greatly.

Note that there are several models that have been used to estimate the FBCF. *The Defense Acquisition Guidebook*, in a chapter entitled "Fully Burdened Cost of Delivered Energy-Methodological Guidance of Analysis of Alternatives, and Acquisition Trade Space Analysis," describes a set of variables which must be considered. These include the cost of fuel itself and the cost of the fuel delivery systems, as well as both a combat performance metric (i.e., which operational stage) and a non-combat "steady state" metric (i.e., peacetime). The seven step calculation process includes: commodity cost of fuel, cost of the primary fuel delivery assets, depreciation of the delivery assets, direct fuel infrastructure and depreciation, indirect fuel infrastructure, environmental cost, and other costs such as force protection. Other models such as Steve Siegal's "Fully Burdened Cost of Fuel Methodology and Calculations for Ground Forces: Sustain the Mission Project 2" incorporate many of the same assumptions and variables and allow for "what if" scenarios and calculations of cost/benefit analyses for alternative energy technologies.

The NRC has just published two studies on energy use in vehicles. One is on fuel economy for light duty vehicles (cars, sport utility vehicles, mini-vans); the second is on medium and heavy vehicles (heavy trucks, buses, semi-tractor trailers). While neither study is specifically directed to Army vehicles, most of the technologies can be applied to one or more categories in the Army's vehicle fleet. The report on light duty vehicles has sections on spark-ignition engines, compression-ignition diesel engines, hybrid power trains, and non-engine technologies. (See Appendix C for the complete table from reference 4.) Estimates are made for likely fuel savings for each technology studied. Some examples are:

- Intake valve modulation and overlap ca. 2%
- Variable valve lifters 10
- Cylinder deactivation 5-10
- Direct gas injection (in header) 1.5-3
- Turbo charging 2-6

These savings are not additive. A key finding in the report is that, overall, there is the potential for fuel savings of from 6 to 11%.

In a section on light weight materials the report states that extensive use of carbon fiber composites has the potential to save up to 50%. It also states that a mass reduction of 5-20% should reduce fuel use by 3-12%.

Unlike light vehicles, most heavy vehicles are designed for moving loads, so the calculation of fuel savings has to be based on a standardized load for each class of vehicles. The report discusses technologies for savings in fuel consumption for a variety of medium and heavy duty vehicles. Application areas: engine technologies for diesel and gasoline engines, transmissions and drive lines, and engine hybrids. Technologies for the rest of the vehicle include aerodynamics, rolling resistance, and vehicle mass.

The report presents potential fuel savings by class of vehicle and by technology areas. Highlights in fuel savings for tractor trailers are:

- engine 20%
- aerodynamics 11.5%
- rolling resistance 11%
- transmission and drive line 7%
- hybrids 10%
- mass 1.25%

For a gasoline powered pickup truck:

- engine 20%
- aerodynamics 3%
- rolling resistance 2%
- transmission and drive train 7.5%
- hybrids 18%
- mass 1.75%

The gasoline engine figure is the potential over and above the current baseline design. Note the dominance of engine technologies and hybrids. (In Appendix D is a complete listing of technologies from reference 11.)

Both reports describe the projected costs to add the new technologies and in some cases the difficulty in manufacturing.

The NRC has also issued two policy studies on energy. In an energy summit of leading thinkers in the field, Amory Lovins is cited to the effect that "seven-eighths of the energy [a vehicle] uses never gets to the wheels. It is consumed in the engine, the driveline, and accessories, as well as in idling. Half of the remaining eighth either heats the tires and road or heats the air through which the car passes. 'Only the last 6 percent actually accelerates the car and then heats the brakes when you stop.' Furthermore, only a twentieth of the mass in a car is the person driving it. The rest is the heavy steel car. So, only 0.3 percent of the fuel burned by an automobile ends up moving the driver. 'This is not very gratifying after 120 years of devoted engineering effort.'[10] Lovins also pointed out that light-weight vehicles made from, for example, carbon fiber components to replace steel, have the potential to increase fuel efficiency of a car by a factor of two. He also maintained that by using a combination of technologies already demonstrated, including light-weight materials, efficiency could be increased by a factor of three.

The second NRC report is a further review of technology options for reducing energy consumption in the US.[11] Part I is a policy review of technical options; Part II is an in-depth assessment of the technologies. Part II is not yet available. The report has a full discussion of the practical barriers to adopting existing and new technologies.

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[10] *The National Academies Summit on America's Energy Future: Summary of a Meeting*. Board on Energy and Environmental Systems, National Research Council, Washington, D.C., 2008.
[11] *America's Energy Future: Technology and Transformation: Summary Edition*, National Academy of Engineering, National Research Council, Washington, D.C., 2009.

The Defense Science Board issued two studies on energy during the past decade. In 2001 the board examined the true cost burden of fuel on the battlefield.[12] Two important findings were (1) that the Department of Defense (DOD) establishes a "standard fuel price" annually. The standard price does not reflect the cost to the Services of delivering the fuel to the ultimate consumer, such as a tank, ship, or aircraft, and (2) that fuel efficiency is not emphasized in the requirements and acquisition processes. This is similar to the point made in reference 2 pertaining to the multiplier that should be used on the refinery cost of fuel. The second report of the Defense Science Board[13] describes the energy consumption of the Defense Department as follows:

> "The Department of Defense is the largest single consumer of energy in the United States. In 2006, it spent $13.6 billion to buy 110 million barrels of petroleum fuel (about 300,000 barrels of oil each day), and 3.8 billion kWh of electricity. This represents about 0.8% of total U.S. energy consumption and 78% of energy consumption by the Federal government. Buildings and facilities account for about 25% of the Department's total energy use. DOD occupies over 577,000 buildings and structures worth $712 billion comprising more than 5,300 sites. In 2006, the Department spent over $3.5 billion for energy to power fixed installations, and just over $10 billion on fuel for combat and combat related systems. These figures exclude energy used by some contractors that performed 'outsourced' DOD functions, but are as accurate as current accounting systems permit."

The Board repeats its earlier recommendations about the need, in the acquisition process for new systems, to consider the true fuel cost burden on the battlefield.

The DSB maintains that there are many promising technologies to improve efficiencies. It urges the DOD to pursue these aggressively and to emphasize battlefield management to take into account the important role that fuel management plays, not just in cost but in the opportunity to reduce the logistics tail and increase the fraction of troops available to fight the war. In addition the report calls attention to the risk involved in depending too much on the commercial electric grid at fixed military installations. The Board is concerned about the fragility of commercial grids and the impact on the military should power be interrupted. The report urges more investment in S&T to speed the development of new energy saving technologies.

In 2007 the Office of Force Transformation and Resources, within the Office of the Under Secretary of Defense for Policy, asked the Logistics Management Institute (LMI)

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[12] *More Capable Warfighting Through Reduced Fuel Burden*, Defense Science Board, Office of the Secretary of Defense, Washington, D.C., 2001

[13] Report of the Defense Science Board Task Force on DOD Energy Strategy, "More Fight – Less Fuel," Defense Science Board, Office of the Secretary of Defense, Washington, D.C., 2008.

to develop an approach to establishing a DOD energy strategy. LMI's report[14] makes the point early on that "DOD's operational concepts seek greater mobility, persistence, and agility for our forces. But, the energy logistics requirements of these forces limit our ability to realize these concepts." This is similar to the points made in all the studies we have reviewed. The report focuses on needed improvements in DODs management policies and practices regarding energy and makes a number of recommendations. The report also says "Make energy a top research and development priority." It recommends that the DOD begin by focusing on three areas:

- Greatest fuel use (aviation forces)
- Greatest logistic difficulty (forward land forces and mobile electric power)
- Greatest warrior impact (individual warfighter burden).

"DOD energy transformation must begin in the near term, addressing current practices and legacy forces, while investing for long-term changes that may radically alter future consumption patterns. We recommend a time-phased approach to reduce our reliance on fossil and carbon-based fuels. This approach includes the following:

- Organizational and process changes that can be implemented immediately
- Engineered solutions, to improve the efficiency of current forces and those nearing acquisition
- Invention of new capabilities, employed in new operational concepts, for those forces yet to be developed."

The LMI report lists a number of technologies and evaluates them in terms of whether they are focused on (1) replacing fossil fuels, (2) reducing demand in military systems, or (3) cross-cutting; i.e., the technologies do both. They are also rated as to near term vs. far term. Details are in Appendix B.

The report places energy challenges in three categories: greatest use, greatest difficulty, and greatest impact. The use category focuses on the demands of aircraft of all types. The difficulty category is operational fuel consumption and mobile electric power. The greatest impact is on battery weight for the soldier. There are brief descriptions of potential candidate technologies but not enough detail for a researcher.

The LMI report is a useful review of energy management, energy policy, and energy technology. It is an example of the utility of a taxonomy in dealing with large numbers of characteristics of a topic and the many potential solutions.[15] The Army has used something like this in its development of its current technical program.

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[14] Thomas D. Crowley, Tanya D. Corrie, David B. Diamond, Stuart D. Funk, Wilhelm A. Hansen, Andrea D. Stenhoff, Daniel C. Swift, *Transforming the Way DOD Looks at Energy: An Approach to Establishing an Energy Strategy*, Logistics Management Institute, Report FT602T1, McLean, VA., 2007.

[17] In Appendix A are three examples of this approach as applies to homeland security challenges (not energy related). These are studies that involved linking a large number of technologies to a broad set of needs or requirements. In all three, a similar kind of taxonomy was used. They began with a set of likely scenarios describing the problems to be addressed followed by a listing of the functional capabilities

We conclude this section by noting once again that the importance of the Nation's and the military's consumption of energy, and in particular of the use of petroleum as fuel, has stimulated a plethora of reviews and analyses, only a small sample of which are cited above. But from this brief look we can learn a great deal. First is the lack of a well-documented basis for calculating the fully burdened cost of fuel. Nonetheless there are large amounts of valuable information. There is solid background on automotive research on fuel efficiency in vehicles. The same is true for power for the dismounted soldier. These technologies are well advanced and many are at the readiness levels required for pursuing fielding opportunities. Technologies for making forward operating bases less dependent on convoys of oil based fuels are less mature; more research and more demonstrations are needed. There are few signs of significant breakthroughs suggesting that more high risk research may be needed.

The Current Army R&D Program

The *Army Warfighter Outcome for Power and Energy* (WOPE)[2] combines into one statement both a broad objective and a brief set of needed capabilities. Presumably the broadest objective would resemble that in several Federal agencies; namely, use less energy by being more efficient, reduce dependence on oil, reduce the cost of energy, and use renewable sources where possible. That would be followed by the functional capabilities one would need to meet the objective and provide some quantitative goals. Here is the WOPE statement as recently amplified for 2011:

"2011 WFO #3. Power & Energy - Enhance ground force effectiveness, flexibility, protection and freedom of movement by reducing the need to transport fuel; improving utility and local management of energy resources; and enhancing unit resilience in the face of uncertain energy situations. Dramatically reduce sustainment footprint, lighten soldier load and extend platform range/self-power endurance by combining component functions, increasing interoperability, improving energy efficiencies and storage densities, and integrating power management functions. Increase flexibility by expanded capabilities to utilize alternative energy sources, recycle energy, water and waste, and to redistribute resources among systems. Reduce size and number of soldiers and systems required in forward areas by deploying multi-function and unmanned systems, and expanding reach capabilities. Integrate power and energy situational awareness and management functions with Mission Command to optimize energy use and enable 'energy-informed operations.'"[18]

The detailed discussion of required capabilities includes the requirements, assessment of the status quo, and proposed solutions for enduring infrastructure, expeditionary base camps, platforms, and the individual soldier. It is a lengthy discussion of the Army's

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required to address these scenario(s). Gaps in capabilities were linked to likely technical approaches. Each technology was then assessed as to readiness, priority, funding needs, and availability of subject matter specialists to move a project forward.

dependence on power and energy at all levels and the need to make significant improvements.

Whereas the LMI study sorted technologies by supply or demand, in this paper we choose to focus on three categories of energy use; namely, vehicles, forward bases, and the dismounted soldier.

Much of the S&T work on power and energy in the Army is carried out in the Army Materiel Command's Research, Development, and Engineering Command (RDECOM). RDECOM has established a set of Technology Focus Teams (TFTs) to help coordinate the technical work done in more than one laboratory or center. Two of these have been especially helpful in preparing this assessment: the Power and Energy TFT led by Dr. John Pellegrino of the ARL, and the Mobility and Logistics TFT led by Dr. Mark Nixon, also of ARL. We received printed material and held interviews with both gentlemen. These have been very helpful.

Some details of the Army's S&T program on power and energy were provided by the Army S&T Executive in June 2010.[16] Dr. Killion discussed added funds from the American Recovery and Reinvestment Act.[17] Some $75 M were provided for research, development, testing, and evaluation in the following areas:

Ground vehicles
Power and energy testing
Silicon carbide
Two new energy facilities
New types of solar photovoltaic systems
Smaller, lighter cogeneration and absorption environmental control systems
Development of field-scale micro grids

Vehicles. For the Army this consists of combat platforms (tanks, combat fighting vehicles, helicopters and unmanned aircraft, Stryker vehicles, and armed HMMWVs) and support vehicles all around the world. The latter are mostly trucks, tankers, and passenger vehicles. These are in support to the battlefield as well as in use at Army installations everywhere. Vehicles consume fuel, oil, and lubricants. The TFT on Mobility and Logistics enumerates work on light-weight stuctures, a number of project areas on engines including advanced cycles, modeling, and thermal management. There is work on combustion of alternate fuels and modeling of combustion. The focus in Army research has been on more efficient engines (diesels, turbines, rotaries, hybrids). Cost is a problem. More efficient turbine engines for the main battle tank have been available for many years but the conversion cost to these or to improved diesels is very high, high enough to have forestalled the investment. Alternatives such as bio-based fuels may

[16] Thomas H. Killion, *Providing Soldiers the Decisive Edge: Power and Energy Technology,* 44th Power Source Conference, Las Vegas, NV, June 2010.
[17] *American Recovery and Reinvestment Act,* The 111th United States Congress, Public Law 111-5, February 17, 2009.

reduce the demand for petroleum but will not reduce the logistics burden and may not reduce the cost either.

Recent emphasis has been on optimized diesel engines where the potential fuel savings may be about 20%. Auxiliary power sources for use in heavy vehicles to save fuel when idling have been studied for many years; one design is scheduled for introduction for the Abrams main battle tank in the near future. Another advantage of using auxiliary power units is that by not idling the main engine they reduce the vehicle's thermal signature. Much of the work on non-combat vehicle technology is either done cooperatively with industry or is adopted from commercial practice. The National Automotive Center (NAC) at the Tank Automotive Research Engineering and Development Center (TARDEC) in Detroit is an important means of collaborating with industry and of moving dual use vehicle technology into the Army. One trend for fuel savings is the conversion of accessory systems such as pumps for power hydraulics, air conditioners, and the like from direct takeoffs from the engine to electric power, thereby only drawing power from the battery/generator when the systems are in use. This is companion to the increased use of hybrid technologies. In the hybrids an electric variable transmission may be used to split power to the drive train and to the electric generation system. (See Side Bar for more details of the NAC program.)

High capacity pulsed power sources are needed for certain weapons and protection capabilities on board platforms: directed energy weapons, electromagnetic armor, and perhaps some form of electrically propelled munitions. There are several approaches, especially capacitor banks or devices with very high rotational velocities. The latter in the form of compulsators (compensated pulsed alternators) have been extensively studied in the Army's electromagnetic gun program. Another approach to storing energy is in high

Industry-Government Initiatives at the National Automotive Center

The National Automotive Center (NAC) is a component of the RDECOM's TARDEC. The NAC is an important means of promoting collaboration between the Army and the automobile industry. The purpose is to share technology of interest to both parties (dual use) and to promote the development of new ideas. The following is from their Web site: NAC will serve as the *Army focal point* for developing *dual-use automotive technologies* and their applications to military ground vehicles. It will focus on *facilitating joint efforts and collaboration among industry, government and academia* in basic research, technology, industrial base development and professional development.[1]

Two initiatives are designed to press adoption of the latest technologies for non-tactical vehicles (automotive and light and heavy duty trucks). The proposal makes the point that across the US – public and private – **"**Medium and heavy trucks make up 4% of all vehicles nationwide, and consume 20% of the nation's vehicle fuel**.** Medium and heavy duty trucks are very important to the Army because they are critical tactical assets and constitute about a quarter of its GSA fleet. Most importantly, the medium/heavy duty truck sector offers the greatest dual-use connection to the tactical fleet." The Advanced Vehicle and Power Initiative is a proposed roadmap for converting the Army current fleet to one using the latest technologies: Qualifying advanced propulsion vehicles for this initiative are battery electric vehicles (BEV), hybrid electric vehicles (HEV), hybrid hydraulic vehicles (HHV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV). The plan is for the Army to phase in these new vehicles over twenty years. It would reduce petroleum consumption by 2% a year until 2030 from a baseline of the use in 2005. This would reduce petroleum demand by 60% from the baseline. Fully realizing the AVPI would require $4.6 billion in funding to offset the cost premium of adopting advanced vehicles and renewable energy systems vs. conventional petroleum-based energy supply systems. The proposal also suggests that excess electric power generated by the fleet could be "exported" to local Army installations.[1]

The second proposal from NAC is an effort to establish a US domestic production base of high-quality advanced automotive battery materials and components that have dual-use applications to both military ground and commercial vehicles by 2015. The proposal argues that most battery manufacturing capability now resides off-shore. The cost of the 5-year program is estimated at about $1 billion.[1]

Neither proposal discusses the technologies in detail, which makes it difficult to evaluate them for challenge and priority against other Army energy S&T work. Two examples of projects done jointly with private sector firms are described in a recent news letter.[1] (*cont. on 17*)

Clandestine Extended Range Vehicle (CERV). An ultra-lightweight prototype devised by the NAC and industry partner Quantum Technology, the CERV is designed for fast-paced mobility operations in the field, including reconnaissance, surveillance, and target designation. Weighing 3,500 pounds and capable of carrying a payload of 2,000 pounds, the CERV incorporates an advanced all-wheel-drive diesel hybrid-electric (HE) power train. The ultra-lightweight chassis allows the CERV to reach speeds of 80 mph and ascend grades of up to 60 percent. The vehicle has a torque rating of 5,000 foot-pounds and reduces fuel consumption by 25 percent compared with conventional vehicles of comparable size.

Electronic Power Control and Conditioning Module (EPCC). Developed between the NAC and industry partner NextEnergy, the EPCC was designed as a battlefield electronics module capable of managing power from varying types or grades of power generation assets, including HEVs, wind turbines, solar panels, and electric generators. The EPCC then cleans and converts the power input into a single, efficient, consistent 50- or 60-hertz alternate current output. Smart Load Interface Controller boxes assist with power management. The EPCC is undergoing testing and could potentially be used to transfer power from HEVs in the field to mobile hospitals and forward operating bases. Skalny believes the EPCC could play an important role in creating energy-independent bases. “At TARDEC, we always talk about energy in terms of layers,” Skalny explained. “While working with partners like NextEnergy for the EPCC, we are looking at concepts like this for national security and energy-independent bases. It’s something that we look forward to from a military standpoint, not just on the tactical vehicles side, but from the non-tactical and administrative side on bases as part of an energy-independent base of vehicles connected to a grid.”

[1] See http://tardec.army.mil/NationalAutomotiveCenter.aspx.

[2] *Advanced Vehicle and Power Initiative*, A Government, Industry and Academia White Paper led by the U.S. Army’s and the Research, Development & Engineering Command’s Tank-Automotive Research, Development & Engineering Center, (TARDEC**),** Draft Four: May 25, 2010.

[3] *Advanced Automotive Battery Initiative*, A Government, Industry and Academia vetted White Paper led by the U.S. Army’s and the Research, Development & Engineering TARDEC**,** Final Version: January 14, 2009.

[4] See http://www.TARDEC.info/GVSETnews, *Army and Industry Partnerships*, GVSET News, TARDEC, Vol. 7, Issue 2 (Mar 2010).

speed flywheels, but such would not appear to be a good way to develop sharp pulses of power.

Power for the Dismounted Soldier. Commanders have long complained of the problems with conventional batteries for the soldier. The various electronic devices that a soldier carries usually require different models of batteries. Often the soldier must carry backup batteries such that the additional load is significant. Commanders want lighter, longer lasting, inexpensive power sources for the soldier. Research programs on the problem have included new forms of storage batteries, especially lithium ion types, and portable fuel cells. Progress over the last thirty years has been remarkable. The energy density of Li-ion batteries has increased by roughly a factor of two in the last decade. It is now in the range of 120 – 200 Wh/kg; by mid-century this may achieve a density of over 700 Wh/kg. These batteries are rechargeable. The higher the energy density the lighter is the load for a given output. The Army continues to develop this technology helped along by the adoption of Li-ion technology in commercial uses such as in electric vehicles and consumer electronics. The work is spread over several laboratories

Work on fuel cells began in the nineteenth century; modern concepts date to the 1950s. Progress has been slow but steady. The Army is studying several designs, including direct methanol, reformed methanol, and polymer exchange membrane cells. Cells operating on methanol without reforming appear to be of most interest. Current status is 30 W/kg (available power draw) and 1,000 Wh/kg (energy density) and projected to 120 W/kg draw. The U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) of the Engineering

Research and Development Center has fielded over 100 fuel cell demonstrations at many different Army installations.[18] These are based on proton exchange membranes or phosphoric acid technologies. An interesting concept is called Silent Camp and involves generating hydrogen by electrolysis of water and then storing the gas until needed for feed to fuel cells.

The Communications-Electronics RDEC (CERDEC) of the RDECOM is working to field portable charging systems based on solar energy for lithium ion batteries as well as a larger system using both solar and wind energy for forward operating bases. CERDEC is also working on lithium carbon fluoride batteries.[19]

Work continues on reducing power demand in electronics; this in turn will reduce the demand on the soldier's power sources.

Forward Operating Bases/Combat Operations Posts. An emerging concept is the convergence of "green practices" such as systemic sustainability and renewable resources with military operational needs. Operations in Southwest Asia have shown that, despite advanced logistics and host nation resources, two major energy related problems persist. The first is that access to fuel, especially during the early expeditionary phase of operations, can be difficult. The second is the cost and operational difficulties posed by waste disposal. Delivery of materiel to forward positions creates enormous volumes of waste, and its removal inflicts a costly and complex logistics and security overhead for U.S. forces. When military operations are viewed as a complex ecosystem, opportunities abound to use one problem (i.e., waste) to help solve the other (i.e., need for energy). Many of the biggest energy sinks such as environmental systems and stoves do not require high quality fuels such as JP-8 and could be run on synthetic gas and biofuels derived from waste-to-energy (WTE) technology. Many packaging materials could be redesigned to use biodegradable materials to further enhance the efficiency of WTE technologies. One experimental technology known as the Tactical Garbage to Energy Refinery, tested by the Army in Iraq, converts about 2,000 pounds of waste per day to synthetic gas and ethanol which are blended to power a 60kW generator set; or the ethanol could be used as fuel for next generation fuel cells.[27] Putting this into perspective, a 550 person Force Provider Unit generates about 2,200 pounds of trash per day, making it an ideal match for this technology. Numerous other WTE and alternate power technologies exist, as do other energy conservation technologies such as "smart" power grids, efficient insulation, and more efficient electronics. The common denominator is to reduce fuel and energy requirements, which reduces the need to transport fuel, saving money and lives.

A major variable is the type of unit or facility using the fuel. As one progresses from Corps level installations to major forward operating bases (FOBs) to smaller FOBs and finally to combat outposts (COPs), the availability of fuel and the uses to which it is put vary greatly. Major installations with fixed or semi-permanent facilities and large

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[18] Information provided from CERL's F.H. Holcomb in an e-mail dated September 29, 2010.
[19] *Jane's International Defence Review*, October 2010, p. 24.

numbers of personnel are power intensive, their daily electrical requirements being measured in megawatts, and use much of that power for air conditioning, stoves and other appliances, hot water, electronics, and major weapons systems. Large FOBs such as Camp Victory, Iraq, with a population of about 25,000 personnel, also generate enormous quantities of garbage including pallets, packing materials, plastic bottles, and food waste which must be disposed of. The Victory Base Camp complex runs eight incinerators continuously, with each consuming about 2,000 gallons of fuel per day. This contrasts with a COP, which typically has no hot water, hot chow, air conditioning, or large-scale waste handling, and where water is a bigger logistics problem than fuel. A battlefield energy audit conducted by the Marine Corps in Afghanistan in August 2009 concluded that seven times as many trucks carried water as fuel.

There are a number of reasons why forward operating bases and combat operations posts should be independent, or nearly independent, of fuel supplied by convoys. First, of course, is to eliminate the exposure of the soldiers operating the convoys—exposures to improvised explosive devices and the like. Second is to reduce the logistics burden on the combat support command in terms of manpower and costs. And third is to enhance the mobility of the bases by reducing their day-by-day dependence on the fixed installations that supply them. Commanders, for example the Marine Commander in Anbar Province in Iraq, have called for reduced reliance on convoys, asking for power supplies based on solar and wind machines.

The Marines have recently been experimenting with a set of components they call the ExFOB. They are currently testing the concepts in Morocco and at a base in California. The idea is to substitute wind and solar energy generators as much as possible for diesel powered generators, and to replace the convoying of bottled water with simple water purification devices using local sources of water. The Natick Soldier RDEC[20] is looking at both sources of energy and demand for it at forward bases. They are looking at solar for both heating and electricity, waste to energy systems, and cogeneration of electricity and useful heat. They are seeking to reduce power demand by a combination of insulation, LED lighting, and flexible photovoltaics for, for example, coatings for tents (a proprietary product for this is called Power Shade). It is being studied by both the Army and the Marines. Natick received special funding for flexible photovoltaics from the American Recovery & Reinvestment Act (the stimulus).

In one study of the best means of handling the disposition of waste at small bases is the use of a combination of gasification and fermentation of the waste to produce two energy rich streams. One, a syngas from the gasifier and alcohols from the fermenter, appeared more attractive than just burying the waste at small installations or incinerating it at large permanent bases. The gases and alcohols contain more than enough energy density to enable their use to drive electric generators.[21] The approach has been demonstrated in

[20] Information provided from NSRDEC's Bindu Nair by an e-mail dated September 29, 2010.
[21] James J. Valdes, Jerry Warner, *Tactical Garbage to Energy Refinery*, EWCBC-TR-713, Edgewood Chemical and Biological Center, Aberdeen Proving Ground, MD, 2009; also see Rebecca C. Wingfield "Waste to Energy Systems," Engineer: The Professional Bulletin for Army Engineers, January-April 2009.

Iraq. Despite the usual difficulties in demonstrating a new process the results were encouraging. The process needs some further engineering and manufacturing investment. There are currently additional programs of converting military waste to energy.[22] Some use pyrolysis of pre-dried solid waste; one uses depolymerization (of plastics and cellulosics by using supercritical water). This one is part of a Defense Advanced Research Projects Agency program called MISER (Mobile Integrated Sustainable Energy Recovery). Unlike the biomass to liquid fuel system from gasification and fermentation, these processes for use in forward operating units stop after the step in which syngas is produced. In these applications the syngas is fed directly into electricity generators.

The above approach to reducing demand for liquid fuels at forward bases is an example of a holistic approach wherein several technologies are integrated to solve the problem. CERL is developing a computer model of the interacting energy systems of a forward base in a project called Virtual FOB.[25] In 2008 the Corps of Engineers conducted a workshop on waste to energy conversion; the report[23] provides a rundown of efforts by or for the Army at that time.

Another means of integrating technologies is the use of microgrids, where electricity users in a local facility are tied together in such a way that management of supply and demand is possible.[24]

Basic Research

Having just presented the current Army R&D program, it is well to look ahead. In the following sections, we look at the Army's basic research efforts, while in the subsequent section we stress the importance of technology forecasting. The paper concludes with some closing remarks and recommendations.

The Army will benefit from more forward-looking research and development in power and energy. Most of the topics being addressed today are evolutionary additions to work that has been in the laboratories for a long time. (An exception is work on biomass to fuel programs, whether from natural biomass or from waste/garbage). Research to push back the frontiers is under way, but in large measure through research awards made by the Army Research Office (ARO).[25] ARO has a broad portfolio of about 30 single investigator research grants to universities and grants to consortia of universities or universities with other private sector laboratories. One such is a portion of the program at

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[22] Leigh Knowlton, "Small Scale Waste to Energy Conversion for Military Field Waste," JSEM Conference, May 2008. See http://proceedings.ndia.org/jsem2008/abstracts/8207.pdf.

[23] F.H. Holcomb, R. Parker, T J. Hartranft, K. Preston, H.R. Sanborn, and P.J. Darcy, *Proceedings of the 1st Army Installation Waste to Energy Workshop*, Engineering Research Development Center, US Army Corps of Engineers, August 2008.

[24] Information in *ERDC-CERL Energy Initiatives*, item 2a, 21 July 2010 from an e-mail provided by F.H. Holcomb, ERDC, CERL, in an e-mail dated September 29,2010.

[25] Information provided by David Skatrud, Army Research Office, in an e-mail dated October 2, 2010.

the Institute of Collaborative Biotechnology (ICB) at the University of California at Santa Barbara. At the ICB there are three energy-related projects in nanomaterials based on biologic principles. One is on bio-inspired large polymeric solar cells, another is on multi-layered nanostructures for new batteries, and a third is on making new membranes with controlled permeability (transport) for ions, electrons, or reactant molecules. ICB has a program on raising the thermal stability of cellulases for application in biomass conversions. ARO single investigator grants on power and energy cover the following categories of work: new materials, catalysis, chemical energy conversion, spectroscopy and optics, and understanding transport through membranes. The work includes batteries and fuel cells, biofuels from algae, and reforming JP8 for fuel for solid oxide fuel cells.[26] Also there is work on solar photovoltaic technology, and ignition and combustion chemistry and physics. The CERL has done work converting solid carbon via pyrolysis to charcoal followed by oxidation by electrolysis in a molten salt.[27]

A Look Forward and the Role of Technology Forecasting

Army researchers were asked to provide us with estimates of where some programs would be in five years. One is the development of microgrids for small installations so that power can be shared among all users. Thus sources with excess power can send it onto the grid for others to use. They need new computer technology and new algorithms. They envision systems converting waste to energy across the Army. As noted in an earlier section, R&D on this is underway.

They estimate that by 2015 we will have vehicles powered by fuel cells and specialty hybrids. Power electronics based on silicon carbide should be improved in terms of producibility, cost, and performance. Alternate energy sources will come on slowly for the battlefield. On-vehicle power supplies for silent watch will be fielded. Work on auxiliary power sources has been in progress for a long time. It should be mature by 2015. These projections will logically be part of a long-range forecast as developed in technology forecasting.

Technology forecasting is a tool that helps shape the S&T portfolio by suggesting where significant developments are likely to occur. In 1992 the NRC published, for the Army, a broad study by experts of the many technical fields estimated to be of interest in the ensuing 25 or 30 years.[28] The effectiveness of the study (STAR21) was evaluated by senior Army subject matter experts in a report published by the National Defense

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[26] Many laboratories are working on solid oxide fuel cells as well as li-ion batteries. A few are noted in *Advanced Materials & Oricesses*, Vol. 168, No. 10, October 2010 on pages 20-21.
[34] R.H. Wolk, S. Lux, S. Gelber, and R.H. Holcomb, *Direct Carbon Fuel Cells: Converting Waste to Electricity*, Construction Engineering Research Center, Engineering Research and Development Center, TR-07-32, September 2007.
[28] STAR21 – Strategic Technologies for the Army of the Twenty-First Century, National Research Council, Washington, D.C., 1992.

University.[29] The results were sufficiently positive that the authors recommended such studies should be conducted every decade and made suggestions for improvements. In two succeeding reports more details were added including the value of using convergence ideas in the forecasting.[30]

Looking for convergence of disparate disciplines is relatively easy in retrospect. An example we have used in the referenced publications is that of radar. The theory of electromagnetic radiation was developed by Maxwell in 1873 and the first experiments by Hertz in 1887. In 1922 reflection of electromagnetic radiation was observed by Navy researchers. However it was not until 1936 that a pulsed radar was built and demonstrated. The necessary adjunct technologies had only matured by this time; that is, the cluster of technologies including radio technologies, radiation sources and receivers, and various components needed to build these systems. Many of these were developed for some other applications but they converged in the realization of radar.

Another example of convergence is the evolution of the long-rod penetrator used in anti-tank munitions. Materials research, penetration mechanics, mechanics of composites, modeling and simulation, sabot design and manufacturing technology – these all matured to make possible the M829A series of kinetic energy rounds, one of which, the Silver Bullet, played a key role in the tank battles in Desert Storm. (See the first paper in reference 37).

The concept of forecasting such convergences is a fairly recent development. A significant report on one such study was published in 2002.[31] In this report convergences were predicted in the fields of nanotechnology, biotechnology, information science, and cognitive science.[32] Research in energy and power for the Army involves many separate disciplines; for example, power, energy, materials, physics, electrical engineering, and perhaps others. Forecasting them individually will not be sufficient to locate new possibilities. Instead the proposal is to compare each forecast with all or some of the others to determine where two or more may come together to enable something new and different to emerge.

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[29] John Lyons, Richard Chait, and Jordan Willcox, *An Assessment of the Science and Technology Predictions in the Army's STAR21 Report*, Defense & Technology Paper 50 (Washington, D.C.: Center for Technology and National Security Policy, National Defense University, July 2008).

[30] John W. Lyons, Richard Chait, and James J. Valdes, *Forecasting Science and Technology for the Department of Defense*, Defense & Technology Paper 71 (Washington, D.C.: Center for Technology and National Security Policy, National Defense University, December 2009); John Lyons, Richard Chait, and Simone Erchov, eds., Defense & Technology Paper 73 (Washington, D.C.: Center for Technology and National Security Policy, National Defense University, September 2010).

[31] The US-NBIC Report: Roco, M.C. and Bainbridge, W.S., eds **(**2002) Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science. National Science Foundation and Department of Commerce, http://www.technology.gov/reports/2002/NBIC/Part1.pdf

[32] *Managing Nano-Bio-Infocogno Innovations: Converging Technologies in Societ*y, edited by William Sims Bainbridge, National Science Foundation, and Mihail C. Roco, National Science Foundation, National Science and Technology Council's Subcommittee on Nanoscale Science, Engineering, and Technology, Springer, 2005.

Assessment and Conclusions

The Army has programs across a spectrum of applications. In this paper we focus on vehicles, dismounted soldiers, and forward bases. (We chose not to look at the vulnerabilities of large fixed bases that rely on external private power grids.) However, the Defense Science Board has expressed concern about this (see reference 13). This problem is not currently in the purview of the Army S&T program at RDECOM, which focuses on operational energy. The lead organization for research for Army installation energy S&T is the CERL. There is much work underway in the three areas in this paper, much of it incremental, building on work that has been underway for a long time. The program clearly addresses the concerns of the TRADOC and is thus in line with the Army's priorities. The internal program on vehicles is consistent, in terms of topics, with discussions in the literature. The focus on batteries and fuel cells for the individual soldier is directed at the most pressing short-term needs. This area has been an active need and an active research program for many years. It now appears that the work is rewarding and the investment is sound; lithium ion batteries are now effective, for example, and promise to be very much more so in the next several years. The concept of reducing the amount of supplies requiring convoys by substituting alternate energy sources is development work focused largely on engineering the needed systems.

Because of the way the programs are organized, there is no easy way to assess quality. Some of the work is subject to peer review in the individual laboratories. But to date there has been no external independent peer review of the effort as a whole.

The effort by RDECOM to pull the power and energy research together has resulted in coverage by two TFTs – one on Power and Energy and one on Mobility and Logistics. Thus the work is not all under one TFT. It would seem that a roadmap covering all the work should be developed as guidance for the portfolio, perhaps through the technology forecasting technique discussed in the previous section.

Recommendations

The following recommendations are made to reinforce the program.

1. *Conduct a formal technology forecasting exercise.* This should take advantage of the convergence approach discussed in an earlier section and discussed in more detail in reference 34. The scope should include the interests of the Corps of Engineers as well as the Army Materiel Command and the TRADOC. The result would be a fairly detailed roadmap showing interactions across individual technology forecasts

2. *More emphasis should be placed on a holistic approach in power and energy, especially for isolated combat operations posts.* It appears that there is demonstrated technology for generating power at isolated posts without hauling fuel over the road. This includes, as partial solutions, solar, wind, and conversion of waste to energy. In addition to work at Natick Soldier Research, Development, and Engineering Center, the Marines have an active program and have been demonstrating it in the field. Perhaps teaming with the Marine Corps would be useful.

3. *The Deputy Assistant Secretary of the Army for Research and Technology should appoint a member of her staff as an overall coordinator of research in Power & Energy.* There is research and development on power and energy in several different sectors of the Army. For example, many laboratories are studying fuel cells and lithium based batteries. Natick and the Core of Engineers share a concern about fuel consumption in forward operating bases. We don't feel that the Army Materiel Command Research Development and Engineering Command's Technology Focus Teams are covering everything across the Army, nor should they. Oversight should include awareness of work done in industry (including recipients of Small Business Innovation Research awards), academe, and other government laboratories.

4. *The Army should review the fully burdened cost of fuel on the battlefield.* The Defense Science Board has emphasized the need to take into account fuel costs as delivered to the warfighter. There are discrepancies in various reports; the acquisition community needs to have a clear picture of these costs.

5. *Seek more integration of fundamental and exploratory research with applied work.* Most of the current effort in the in-house laboratories is either incremental extensions in existing areas of research or is engineering of systems. However, the Army Research Office (ARO) has a broad program of research in this area. More emphasis should be placed on strengthening the relationships between in-house programs and those at ARO. To enhance the creativity of the work, more basic research investment should be made.

6. *The subject matter experts in the Army laboratories should devote some attention to the work of various components of the National Academies.* It is surprising that the Army's White Paper (reference 2) does not cite any of the several studies on power and energy published by various committees of the National Research Council. These reports (see references 7 through 12 above) are comprehensive and produced by selected experts from across the country. They are most informative. The subject matter experts should be actively involved in the technology forecasting activity.

We believe that these recommendations will help the Army in dealing with the difficulties involved in providing power and energy to the warfighter on the battlefield.

Appendices

Appendix A. Taxonomy for Assessment and Forecasting

An example of a taxonomy involving several operational challenges and a number of possible technical responses is Project Responder, a study arising from the terrorist bombing of the Murrah Federal Building in Oklahoma City in 1995.[33] The other two studies were on Army–Department of Homeland Security cooperation in technology.[34,35] Each study began with a set of operational problems presented by terrorism in the homeland. A set of scenarios illustrated the challenges. The scenarios defined the required functional capabilities and these were followed by posing technological remedies. With this systematic approach, the results of analyses by panels of experts were presented in tables.

As an example from report reference 25, the four operational areas in homeland security were defined by the DOD (before DHS became operational): indications and warnings, denial and survivability, recovery and consequence management, and attribution and retaliation. For each operational area, the report describes the priority functional capabilities required, followed by consideration of applicable technologies and their availability. This was followed by an assessment of readiness, priority for Army funding, and suitability for Army, DHS, or civilian use.

Here is a sample line taken from a table from reference 25 under “indications and warnings”:

Indications and Warnings >
  Perimeter defense and warning>
    Night vision>
      Uncooled bolometer arrays>
        Ready or near term>
          High priority for S&T>
            Broadly useful for all

[33] *Project Responder, National Technology Plan for Emergency Response to Catastrophic Terrorism,* edited by Thomas M. Garwin, Neal A. Pollard, and Robert V. Tuohy, Hicks & Associates, Inc., Tyson’s Corner, VA., 2004.
[34] National Research Council, *Science and Technology for Army Homeland Security: Report 1,* The National Academies Press, Washington, D.C., 2003.
[35] National Research Council, *Army Science and Technology for Homeland Security, Report 2 C4ISR,* The National Academies Press, Washington, D.C., 2004

Appendix B. Listing of Technologies from the Logistics Management Institute

The tables are from Table 6-1 and Appendix F of reference 16. Tables 6-1 and Appendix F-1 are reprinted with permission from the Logistics Management Institute. Copyright 2007.

Table 6-1. Energy Change Options

Technology	Options		
	Near term		Far term
	Organize	Engineer	Invent
Supply (replace fossil fuels)			
Synthetic fuels		Coal and natural-gas-based fuels (Fischer-Tropsch process)	Synthetics from renewable resources
Biofuels		Replacing conventional fuels with biofuels, including biodiesel Optimizing future applications to run on biofuels	Microalgae or other high-energy biofuels
Hydrogen		Hydrogen combustion	Fuel-cell powered applications Portable soldier power
Nuclear power		Naval propulsion Nuclear power sources for synthetic fuel production	Nuclear power sources for hydrogen fuel production Advanced nuclear propulsion (reduced size, manpower)
Geothermal energy		Nontactical use in favorable geographies	
Demand (reduce fuel consumption)			
Engines/ turbines		Auto shutoff and partial engine idling Reengineering of aircraft and tanks Low-emission diesel Low-speed turbofan aircraft engines	Low-temperature combustion mode engines
Materials		Composites and lightweight metals for aircraft, ships, and vehicles	Advanced lightweight armor
Hybrid drive		Hybrid vehicles	Advanced hybrid systems
Unmanned vehicles	Increased use of unmanned vehicles in place of manned vehicles	Improved unmanned vehicles	Advanced autonomous unmanned vehicles
Aerodynamic design/ blended-wing aircraft		Aerodynamic enhancements to current airframes	Blended-wing aircraft designs
More-electric architecture		Replacing mechanical and hydraulic components with electric for aircraft, ships, and ground vehicles	

Table 6-1. Energy Change Options

Technology	Options		
	Near term		Far term
	Organize	Engineer	Invent
Information technology/ information management	Efficient scheduling Simulators and virtual training Increased reach-back	Monitoring and control systems Air traffic management	Control of hybrid systems Information capture for future improvement
Low-power computing		System on Chip (SoC) technologies	Power Aware Computing and Communication (DARPA)
Cross-cutting (replace local supply and reduce logistics demand)			
Batteries	Replacing primary with secondary batteries	Battery charge indicators Upgrading batteries to best available chemistry	Next-generation batteries
Generators		More efficient battlefield generators	Micro-turbines Portable fuel cell battery chargers
Fuel cells		Stationary power	Ship service fuel cells Reforming JP-8 for port-able power Battery-sized fuel cells for portable electronics Hydrogen infrastructure
Solar		Solar collector installation	Space-based solar
Wind		Wind turbine installation	
Ocean energy		Ocean thermal energy conversion	Surface and ocean wave energy harvesting
Conversion of waste-to-energy		Direct conversion of waste to electricity	Conversion to liquid fuels via pyrolysis

Table F-1. LMI Workshop Energy Investment Rankings
(From January 24, 2007, Energy Technology Assessment Workshop)

Technology	Count | Priority Score (L*1, M*2, H*3)						No Response	Mean Score
	High		Medium		Low			
Bulk energy for direct or indirect liquid fuel replacement								
Solar	3	9	0	0	1	1	1	2.5
Hydrogen	2	6	1	2	1	1	1	2.3
Synthetic fuels	2	6	1	2	2	2	0	2.0
Bio-based fuels	2	6	1	2	2	2	0	2.0
Geothermal	0	0	3	6	1	1	1	1.8
Ocean wave	1	3	1	2	3	3	0	1.6
Nuclear	1	3	0	0	3	3	1	1.5
MEAN bulk energy for direct or indirect liquid fuel replacement								1.9
Local energy supply -- fuel distribution avoidance								
Solar	3	9	2	4	0	0	0	2.6
Improved batteries	4	12	0	0	1	1	0	2.6
Waste-to-energy	2	6	2	4	0	0	1	2.5
Fuel cells	3	9	0	0	1	1	1	2.5
Nuclear	1	3	0	0	2	2	2	1.7
In-theater syn or bio fuel production	0	0	1	2	2	2	2	1.3
MEAN local energy supply -- fuel distribution avoidance								2.2
Demand reduction -- fuel distribution avoidance								
Unmanned vehicles	5	15	0	0	0	0	0	3.0
Lightweight metals and composites	5	15	0	0	0	0	0	3.0
Virtual training/simulators	5	15	0	0	0	0	0	3.0
More efficient design: Aerodynamic design	4	12	0	0	0	0	1	3.0
Engine development	3	9	1	2	0	0	1	2.8
Improved IT/IM	2	6	1	2	0	0	2	2.7
More efficient design: Blended wing aircraft	3	9	0	0	1	1	1	2.5
Hybrid technologies	3	9	1	2	1	1	0	2.4
More-electric architecture (MOE)	0	0	2	4	1	1	2	1.7
MEAN demand reduction -- fuel distribution avoidance								2.7
				STDEV		0.5	MEAN	2.3

Appendix C

Summary table from NRC report on light duty vehicles (Ref. 10). Table S-1 is reprinted with permission from the National Academies Press, Copyright 2010, National Academy of Science.

TABLE S-1 Committee's Estimates of Effectiveness (shown as a percentage) of Near-Term Technologies in Reducing Vehicle Fuel Consumption

Technologies		Incremental values - A preceding technology must be included								
		I4			V6			V8		
Spark Ignition Techs	Abbreviation	Low	High	AVG	Low	High	AVG	Low	High	AVG
Low Friction Lubricants	LUB	0.5	0.5	**0.5**	0.5	0.5	**0.5**	0.5	0.5	**0.5**
Engine Friction Reduction	EFR	0.5	2.0	**1.3**	0.5	2.0	**1.3**	1.0	2.0	**1.5**
VVT- Coupled Cam Phasing (CCP), SOHC	CCP	1.5	3.0	**2.3**	1.5	3.5	**2.5**	2.0	4.0	**3.0**
Discrete Variable Valve Lift (DVVL), SOHC	DVVL	1.5	3.0	**2.3**	1.5	3.0	**2.3**	2.0	3.0	**2.5**
Cylinder Deactivation, SOHC	DEAC	NA	NA	NA	4.0	6.0	**5.0**	5.0	10.0	**7.5**
VVT - In take Cam Phasing (ICP)	ICP	1.0	2.0	**1.5**	1.0	2.0	**1.5**	1.5	2.0	**1.8**
VVT - Dual Cam Phasing (DCP)	DCP	1.5	2.5	**2.0**	1.5	3.0	**2.3**	1.5	3.0	**2.3**
Discrete Variable Valve Lift (DVVL), DOHC	DVVL	1.5	3.0	**2.3**	1.5	3.5	**2.5**	2.0	4.0	**3.0**
Continuously Variable Valve Lift (CVVL)	CVVL	3.5	6.0	**4.8**	3.5	6.5	**5.0**	4.0	6.5	**5.3**
Cylinder Deactivation, OHV	DEAC	NA	NA	NA	4.0	6.0	**5.0**	5.0	10.0	**7.5**
VVT - Coupled Cam Phasing (CCP), OHV	CCP	1.5	3.0	**2.3**	1.5	3.5	**2.5**	2.0	4.0	**3.0**
Discrete Variable Valve Lift (DVVL), OHV	DVVL	1.5	2.5	**2.0**	1.5	3.0	**2.3**	2.0	3.0	**2.5**
Stoichiometric Gasoline Direct Injection (GDI)	SGDI	1.5	3.0	**2.3**	1.5	3.0	**2.3**	1.5	3.0	**2.3**
Turbocharging and Downsizing	TRBDS	2.0	5.0	**3.5**	4.0	6.0	**5.0**	4.0	6.0	**5.0**
Diesel Techs										
Conversion to Diesel	DSL	15.0	35.0	**25.0**	15.0	35.0	**25.0**	NA	NA	NA
Conversion to Advanced Diesel	ADSL	7.0	13.0	**10.0**	7.0	13.0	**10.0**	22.0	38.0	**30.0**
Electrification/Accessory Techs										
Electric Power Steering (EPS)	EPS	1.0	3.0	**2.0**	1.0	3.0	**2.0**	1.0	3.0	**2.0**
Improved Accessories	IACC	0.5	1.5	**1.0**	0.5	1.5	**1.0**	0.5	1.5	**1.0**
Higher Voltage/Improved Alternator	HVIA	0.0	0.5	**0.3**	0.0	0.5	**0.3**	0.0	0.5	**0.3**
Transmission Techs										
Continuously Variable Transmission (CVT)	CVT	1.0	7.0	**4.0**	1.0	7.0	**4.0**	1.0	7.0	**4.0**
5-spd Auto. Trans. w/ Improved Internals		2.0	3.0	**2.5**	2.0	3.0	**2.5**	2.0	3.0	**2.5**
6-spd Auto. Trans. w/ Improved Internals		1.0	2.0	**1.5**	1.0	2.0	**1.5**	1.0	2.0	**1.5**
7-spd Auto. Trans. w/ Improved Internals		2.0		**2.0**	2.0		**2.0**	2.0		**2.0**
8-spd Auto. Trans. w/ Improved Internals		1.0		**1.0**	1.0		**1.0**	1.0		**1.0**
6/7/8-spd Auto. Trans. w/ Improved Internals	NAUTO	3.0	8.0	**5.5**	3.0	8.0	**5.5**	3.0	8.0	**5.5**
6/7-spd DCT from 4-spd AT	DCT	6.0	9.0	**7.5**	6.0	9.0	**7.5**	6.0	9.0	**7.5**
6/7-spd DCT from 6-spd AT	DCT	3.0	4.0	**3.5**	3.0	4.0	**3.5**	3.0	4.0	**3.5**
Hybrid Techs										
12V BAS Micro-Hybrid	MHEV	2.0	4.0	**3.0**	2.0	4.0	**3.0**	2.0	4.0	**3.0**
Integrated Starter Generator	ISG	29.0	39.0	**34.0**	29.0	39.0	**34.0**	29.0	39.0	**34.0**
Power Split Hybrid	PSHEV	24.0	50.0	**37.0**	24.0	50.0	**37.0**	24.0	50.0	**37.0**
2-Mode Hybrid	2MHEV	25.0	45.0	**35.0**	25.0	45.0	**35.0**	25.0	45.0	**35.0**
Plug-in hybrid	PHEV	NA	NA	NA	NA	NA	NA	NA	NA	NA
Vehicle Techs										
Mass Reduction - 1%	MR1	0.3		**0.3**	0.3		**0.3**	0.3		**0.3**
Mass Reduction - 2%	MR2	1.4		**1.4**	1.4		**1.4**	1.4		**1.4**
Mass Reduction - 5%	MR5	3.0	3.5	**3.3**	3.0	3.5	**3.3**	3.0	3.5	**3.3**
Mass Reduction - 10%	MR10	6.0	7.0	**6.5**	6.0	7.0	**6.5**	6.0	7.0	**6.5**
Mass Reduction - 20%	MR20	11.0	13.0	**12.0**	11.0	13.0	**12.0**	11.0	13.0	**12.0**
Low Rolling Resistance Tires	ROLL	1.0	3.0	**2.0**	1.0	3.0	**2.0**	1.0	3.0	**2.0**
Low Drag Brakes	LDB	1.0		**1.0**	1.0		**1.0**	1.0		**1.0**
Aero Drag Reduction 10%	AERO	1.0	2.0	**1.5**	1.0	2.0	**1.5**	1.0	2.0	**1.5**

NOTE: Some of the benefits (highlighted in the table) are incremental to those obtained with preceding technologies shown in the technology pathways described in Chapter 9.

Appendix D

Three tables from NRC report on medium and heavy duty vehicles (Ref 11.). Table S-1, S-2, and S-3 are reprinted with permission from the National Academies Press, Copyright 2010, National Academy of Science.

TABLE S-1. Range of Fuel Consumption Reduction Potential, 2015-2020, for Powertrain Technologies

Technology	Fuel Consumption Reduction, %
Diesel engines	15 to 21
Gasoline engines	up to 24
Diesel over gasoline engines	6 to 24
Improved transmissions	4 to 8
Hybrid powertrains	5 to 50

Note: Potential fuel reductions are not additive. For each vehicle class, the fuel consumption benefit of the combi technology packages is calculated as follows: [%$FCR_{package}$ = 100 [1 – (1 – {% FCR_{tech1} /100 }) (1 – {% FCR_{tech2}/100)} … (1 – {% FCR_{techN}/100 })]. Values shown are for one set of input assumptions. Results will vary depending on these assumptions.

TABLE S-2. Range of Fuel Consumption Reduction Potential, 2015-2020, for Vehicle Technologies

Technology	Fuel Consumption Reduction, %
Aerodynamics	3 to 15
Auxiliary loads	1 to 2.5
Rolling resistance	4.5 to 9
Mass (Weight) reduction	2 to 5
Idle reduction	5 to 9
Intelligent vehicle	8 to 15

Note: Potential fuel reductions are not additive. For each vehicle class, the fuel consumption benefit of the combined technology packages is calculated as follows: [%$FCR_{package}$ = 100 [1 – (1 – {% FCR_{tech1} /100 }) (1 – {% FCR_{tech2}/100)} … (1 – {% FCR_{techN}/100 })]. Values shown are for one set of input assumptions. Results will vary depending on these assumptions.

SOURCE: Adapted from TIAX (2009).

TABLE S-3. Fuel Consumption Reduction Potential for Typical New Vehicles in 2015–2020 and Effectiveness Comparisons for Seven Vehicle Configurations

Vehicle Class	Fuel Consumption Reduction, %	Capital Cost, $	Cost Effectiveness Metric		
			$/% Fuel Saved	Dollars per gal. Saved per Year	Breakeven fuel price,[a] $/gal.
Tractor-trailer	51	84,600	1,670	7.70	1.10
Class 6 box truck	47	43,120	920	29.30	4.20
Class 6 bucket truck	50	49,870	1,010	37.80	5.40
Class 2b pickup	45	14,710	330	33.70	4.80
Refuse truck	38	50,800	1,320	18.90	2.70
Transit bus	48	250,400	5,230	48.00	6.80
Motor coach	32	36,350	1,140	11.60	1.70

[a] Calculated assuming a 7 percent discount rate and a 10-year life, excluding incremental operating and maintenance costs associated with the technologies. NOTE: Numbers in last three columns are rounded. Also, these point estimates will vary depending on input assumptions. For each vehicle class, the fuel consumption benefit of the combined technology packages is calculated as follows: [$\%FCR_{package} = 100\ [1 - (1 - \{\%\ FCR_{tech1}/100\})\ (1 - \{\%\ FCR_{tech2}/100)\} \ldots (1 - \{\%\ FCR_{techN}/100\})]$. Values shown are for one set of input assumptions. Results will vary depending on these assumptions.

SOURCE: Adapted from TIAX (2009).